Photoproduction of Θ^+ via the $\gamma D \to \Theta^+\Lambda$ reaction

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ABSTRACT

We propose to produce the Θ^+ and measure its width via the strangeness tagging two body photoproduction reaction:

$$\gamma D \rightarrow \Theta^+\Lambda, \quad \Lambda \rightarrow p\pi^-, \quad \Theta^+ \rightarrow K^+n.$$

The proposal is to perform a triple coincidence measurement of the proton and negative pion from the Λ decay, and the K^+ from the Θ^+ decay. The Λ and Θ^+ are produced by a bremsstrahlung photon beam incident on a deuterium cryogenic target in Hall A.

In the measured missing mass distribution, at the known mass of about 1540 MeV$/c^2$, we expect to identify a narrow peak of 370-3700 events (for Θ^+ widths of 1-10 MeV respectively). The mass reconstruction resolution of about 2.5 MeV, the ratio of signal/background, and the expected statistics should allow us to determined the width of the Θ^+ to an accuracy of about 2 MeV. Even if the production cross section is an order of magnitude smaller than the calculations, the Θ^+ peak in the missing mass can be identified and its width can be determined for widths of 2 MeV and above. The total requested beam time is 160 hours.

The proposed measurement utilizes the special features of Hall A. The experiment uses existing equipment, such as the photon radiator, the Hall A deuterium cryogenic target, one of the two HRS spectrometers to detect the proton, an array of plastic scintillators to detect the π^-, and the BigBite spectrometer to measure the K^+. There are only relatively minor modifications and adjustments needed to the equipment mentioned above to make it appropriate for the proposed measurement.

1 Scientific Background and Motivation

1.1 Experimental Overview

Several experiments have recently claimed to observe an exotic $S = 1$ baryon resonance with a mass of about 1540 MeV/c^2 and a very narrow width. A baryon with a positive strangeness cannot be a 3 quark state. This resonance, called Θ^+, must have a minimal quark content of $uudd\bar{s}$ (pentaquark).

The first claim was by the SPRING-8 LEPS / Osaka group that found a peak of 19 events in the missing mass spectrum of the $\gamma^{12}C \rightarrow K^-\Theta^+$ reaction [1]. The measured width of this peak is below the experimental resolution and is claimed to be below 25 MeV. The statistical significance is claimed to be 4.6σ.

A peak at the same mass (1542 ± 5 MeV/c^2) was also observed by the CLAS collaboration using the $\gamma D \rightarrow K^+K^-pn$ reaction [2]. The measured width in this measurement was 21 MeV, equal to the experimental resolution. The 43 events over the background are claimed to produce a statistical significance of 5.8σ.

In a more recent analysis the CLAS collaboration studied photoproduction on a hydrogen target[3]. After applying strong angle cuts on their data they claimed to observe a Θ^+ peak in the $\pi^+K^-K^+(n)$ and the $K^0K^+(n)$ final states. The first is an excess of 41 events, at a mass of 1555 ± 10 MeV/c^2 with a width smaller than 28 MeV. The second is a peak at 1571 ± 4 MeV/c^2 with a width less than 9 MeV. The statistical significance of these peaks is claimed to be 7.8σ and 6.4σ respectively.

The DIANA/ITEP collaboration analyzed bubble-chamber data for Xe(K^+, K^0p) and announced the discovery of a narrow peak at 1539 ± 2 MeV/c^2 with a statistical significance of 4.4σ and width which is less than 9 MeV [4].

The DIANA collaboration also report observation of the Θ^+ decay to K_s^0p in neutrino interactions with nuclei [5]. The peak from the combined deuterium and neon target is claimed to have 27 events, a mass of 1533 ± 5 MeV/c^2, a width of less than 29 MeV, and a statistical significance of 6.7σ. The cross section for Θ^+ production appears to increase with atomic number of the target.

Using the SAPHIR detector at the ELSA accelerator (Bonn), the collaboration claimed an observation of a peak in the photoproduction of the $nK^+K_s^0$ final state on protons [6]. The peak with a mass of 1540 ± 4 MeV/c^2 and width below 25 MeV is claimed to have 63 events and statistical significance of 4.8σ. A similar peak is missing from the pK^+ invariant mass spectrum which leads the authors to conclude that the Θ^+ is isoscalar.

The HERMES collaboration reported, in a recent workshop, evidence for the Θ^+ in quasi-real photo production on deuterium followed by decay to $pK_s^0 \rightarrow p\pi^+\pi^-$ [7]. The 72 events detected have a missing mass of $1526 \pm 2 \pm 2$ MeV/c^2 (about 2σ bellow the world average from 5 other measurements), a width of less that 20 MeV and statistical significance of 5.6σ. This collaboration also reports the lack of a peak in the K^+p invariant mass spectrum.

In the recent pentaquark workshop at Jefferson Lab, the GRAAL collaboration presented preliminary results from $\gamma D \rightarrow 6\gamma + p + n$ [8]. They look for the reaction $\gamma D \rightarrow \Theta^+\Lambda^*$. The preliminary invariant mass spectra is claimed to show a peak of about 20 events at about 1540 MeV/c^2.

In Summary: it is clear that if the Θ^+ exists, it has already been discovered. We know it has a mass of about 1540 MeV/c^2 and a width of less that 10 MeV. This was clearly established by the first generation measurements reported above.

All together, in all the measurements reported above, there are less than 200 candidate Θ^+ events, without even one measurement with at least 100 events. It is clear that a convincing peak of a few hundred events is necessary to confirm the discovery. This is a primary goal of the already approved A-rated Hall B experiment E03-113. The production mechanisms in some of the experiments are quite complicated and there are possibilities of kinematical reflections resulting from other decays[9]. Other reactions in particular simple two body reactions are also desired to be convinced that the peaks are really due to Θ^+ production. The experiments mentioned above, even if they have detected the Θ^+, did not establish its width, except for an upper limit that it is below 10 MeV. They also do not allow determination of the spin and parity of the Θ^+.

The second generation of experiments, of which this proposal is one, have now to achieve the following goals:

- Confirm the existence of the Θ^+ with a clear peak of at least hundreds of events that can unambiguously be identified at a fixed mass in the K^+N system rather than as some kinematical/experimental reflection of something else.
- Determine the width of the Θ^+ or reduce the upper limit by about an order of magnitude (to of order 1 MeV).
- Determine the spin, parity, and isospin of the Θ^+.
- Find more states of the same family.

We claim here that this proposed experiment will allow us to achieve the first two goals on the list.

1.2 Theoretical Overview

Skyrme proposed a way of looking at baryons as soliton solutions of a pionic field. In the large N_c limit, this chiral soliton model approximates QCD. In this model there are three SU(3) flavor multiplets: an octet ($1/2^+$), a decuplet ($3/2^+$) and an anti-decuplet ($1/2^+$). The latter includes states with exotic quantum numbers. Using this model Diakonov, Petrov and Polyakov[10] predicted the existence of a narrow resonance with a mass of about 1.53 GeV/c^2, strangeness +1, spin=1/2 and positive parity. This is an isosinglet; it is the lowest mass member of the anti-decuplet mentioned above. If the Θ^+ is proven to have these predicted quantum numbers, it will be a remarkable achievement of this approach. If on the other hand the parity of the Θ^+ is found to be negative it will be very hard to understand it in this context.

The quark model explains that the baryon states of 3 quarks are organized in an octet and decuplet of $J^\pi = 1/2^+$ and $3/2^+$ respectively. In QCD, states with 4 quark and one anti quark with a flavor different from the 4 quarks (pentaquarks) are not forbidden. The structure of these exotic baryons in the quark model is not clear. In a recent work, Karliner and Lipkin[11] proposed an interpretation of the Θ^+ as an isoscalar color antitriplet diquark (ud) coupled to an isoscalar color triplet triquark (uds) with one unit of relative orbital angular momentum between the clusters. Jaffe and Wilczek[12] proposed a different structure of two highly correlated diquarks (ud) and an antiquark. It is not clear that any of these models can quantitatively explain a narrow width of about 1 MeV or less, if found for the Θ^+.

The microscopic models mentioned above are different in important ways that relate to our lack of understanding of strong color field forces and of the correlations that are produced in baryons. Experimental studies of Θ^+ properties, and the discovery and study of the properties of the other members of its family, will allow a better understanding of these issues. *Achieving the goals mentioned above for the experimental program will end in a breakthrough in our understanding of baryon spectroscopy and the strong interaction at large.*

1.3 Calculation of Production and Background Cross Sections

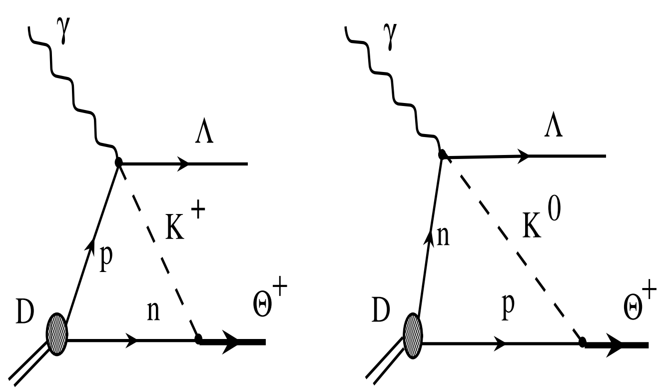

Figure 1: Two diagrams describing the reaction $\gamma + D \to \Lambda + \Theta^+$ reaction.

Production of the Θ^+ on deuterium can occur via several different reactions. Here we consider a strangeness tagging mechanism with the reaction $\gamma + D \to \Lambda + \Theta^+$ (see Figure 1). The main advantage of this mechanism is that the theoretical analysis of the reaction is to a large extent model independent: the differential cross section for $\gamma + p \to \Lambda + K^+$ has been measured and the $\gamma + p \to \Lambda + K^+$ and $\gamma + n \to \Lambda + K^0$ amplitudes have been phenomenologically parameterized; the deuteron wave function is known very well; the dynamical information about the Θ^+ enters only through one unknown parameter, the total width of Θ^+. The main disadvantage of this reaction is that the Θ^+ production takes place through rescattering on the spectator nucleon of deuterium resulting a significant suppression by the nuclear form factor.

The reaction $\gamma + D \to \Lambda + \Theta^+$ is described by the two Feynman diagrams shown in Figure 1. The resulting amplitude depends crucially on the interference between the $\gamma\, p \to \Lambda\, K^+$ and $\gamma\, n \to \Lambda\, K^0$ scattering amplitudes.

In our theoretical analysis of the Feynman diagrams in Figure 1, we assume that the resulting amplitude is predominantly imaginary. The imaginary part is found as a sum of all possible cuts of the diagrams in Figure 1. It is clear that there are three possible cuts. However, cutting simultaneously the spectator nucleon and kaon lines gives the dominant contribution. This cut places the spectator nucleon and the kaon on the mass shell.

It is important to emphasize that in the $\Theta^+ \to NK$ vertex all particles are on mass shell. This means that this part of the amplitude is a function of the particle masses and the total width of Θ^+ but, it does not depend on the spectator momentum.

The $\gamma + N \to \Lambda + K$ vertex depends on the nucleon momentum. For simplicity, we assumed that this vertex depends on some average spectator momentum. With this assumption the corresponding scattering amplitude is completely determined by the external kinematics. For the amplitudes $\gamma + p \to \Lambda + K^+$ and $\gamma + n \to \Lambda + K^0$ and their sum we used the results of the MAID generator [13].

The differential cross section for the $\gamma + D \to \Lambda + \Theta^+$ process can be factorized to the form:

$$\frac{d\sigma^{\gamma+D\to\Lambda+\Theta^+}}{dt} = 2\pi\Gamma^{\rm tot}\frac{M_\Theta^3}{\sqrt{(M_\Theta^2 - m^2 - M_K^2)^2 - 4m^2M_K^2}}\frac{d\sigma^{p+n}}{dt}S(t)^2\,, \tag{1}$$

where t is the momentum transfer at the $\gamma N \to \Lambda + K$ vertex, $t = (p_\gamma - p_\Lambda)^2$.

The first factor comes from the $\Theta^+ \to NK$ vertex. The width of the Θ^+ is not known and we treat it as a free parameter. Given the upper limit from the measurements discussed above, we will carry the numerical analysis for $\Gamma^{\rm tot} = 1$, 2, 5, and 10 MeV.

The differential cross section $d\sigma^{p+n}/dt$ includes the $\gamma + p \to \Lambda + K^+$ and $\gamma + n \to \Lambda + K^0$ amplitudes and their interference. The differential cross section, $d\sigma^{p+n}/dt$, at the photon beam energy, 1.2 GeV, is presented in Figure 2 (solid curve). For comparison, we also give the $\gamma + p \to \Lambda + K^+$ differential cross section (dashed curve).

Note that at small values of t, $d\sigma^{p+n}/dt$ is significantly larger than $d\sigma^{p}/dt$, which enhances the $\gamma + D \to \Lambda + \Theta^+$ cross section. We have checked that the MAID results are consistent with the SAPHIR $\gamma + p \to \Lambda + K^+$ data.

The factor $S(t)^2$ in Eq. (1) describes the t-dependent suppression due to the deuteron form factor. For the deuteron wave function, we used the Paris nucleon-nucleon potential. Figure 3 presents $S(t)^2$ as a function of t.

The differential cross section for the $\gamma + D \to \Lambda + \Theta^+$ process, which is given by Eq. (1), is presented in Figure 4.

The cross section is largest at $t \approx -0.1$ (GeV/c)^2, which corresponds to a 20° scattering angle of the Λ in the laboratory reference frame. The strong t-dependence resulting from both $S(t)^2$ and $d\sigma^{p+n}/dt$ suggests that the region around $t = -0.1$ (GeV/c)^2 is most favorable for the experimental studies of the $\gamma + D \to \Lambda + \Theta^+$ reaction.

Integrating the differential cross section over t, we obtain for the integrated cross section at $E_g = 1.2$ GeV:

$$\sigma^{\gamma+D\to\Lambda+\Theta^+} = 0.7 \times \Gamma^{\rm tot}\text{nbarn}\,. \tag{2}$$

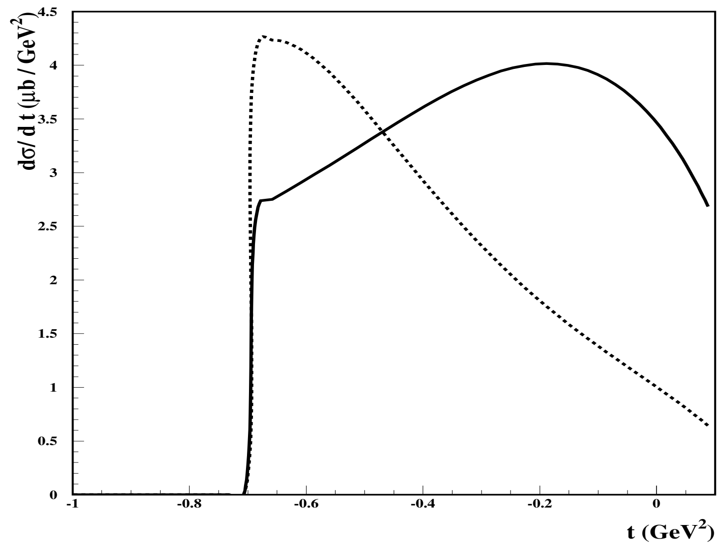

Figure 2: The $\gamma + p \to \Lambda + K^+$ + $\gamma + n \to \Lambda + K^0$ differential cross sections $d\sigma^{p+n}/dt$ (solid curve) and the $\gamma + p \to \Lambda + K^+$ differential cross section (dashed curve).

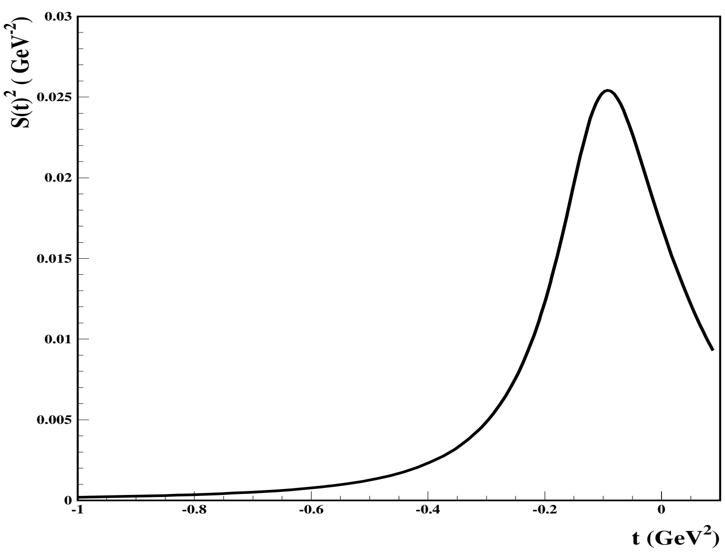

Figure 3: The nuclear suppression factor $S(t)^2$.

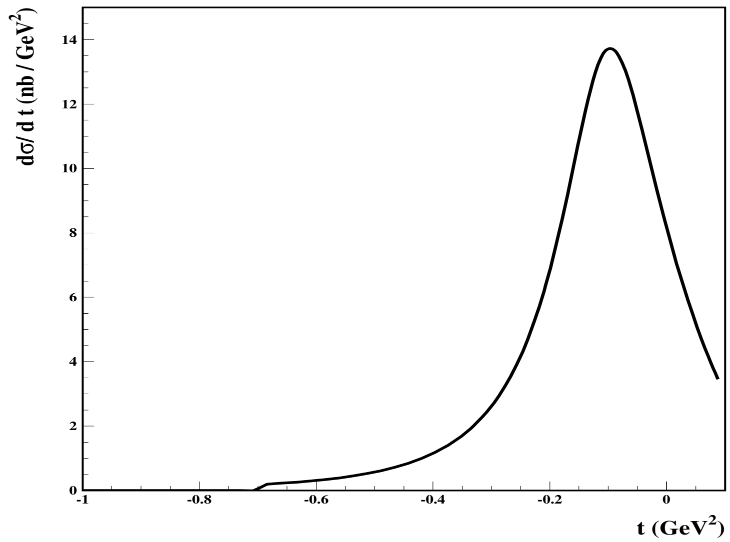

Figure 4: The $\gamma + D \to \Lambda + \Theta^+$ differential cross section. The calculation in the figure is for $\Gamma^{\rm tot} = 5$ MeV.

We also estimate the rate of the background reaction $\gamma + D \to \Lambda + K + N$, shown in Figure 5.

We calculated the differential cross section for this background reaction with a constraint on the invariant mass of the Kaon-nucleon system to be:

$$M_\Theta - 0.010\,\mathrm{GeV} \le M_{KN} \le M_\Theta + 0.010\,\mathrm{GeV}\,. \tag{3}$$

The resulting $\gamma + D \to \Lambda + K^+ + n$ differential cross section is presented in Figure 6 by the dashed curve. This curve should be compared to the differential cross section for $\gamma + D \to \Lambda + \Theta^+ \to \Lambda + K^+ + n$. The latter (the solid curve in Figure 6) is obtained by scaling down by a factor of two the curve of Figure 4 for the $\gamma + D \to \Lambda + \Theta^+$ reaction.

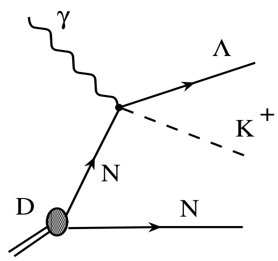

Figure 5: The background reaction.

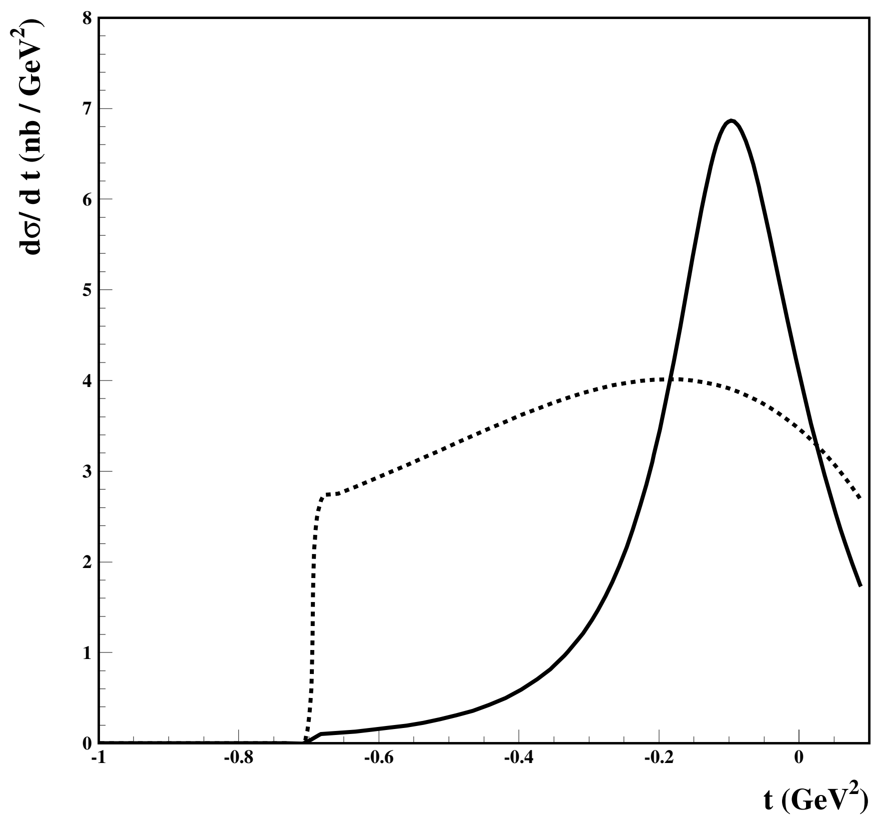

Figure 6: Half the Θ^+ photoproduction cross section for the $\gamma + D \to \Lambda + \Theta^+ \to \Lambda + K^+ + n$ reaction (solid curve) compared with the background reaction $\gamma + D \to \Lambda + K^+ + n$ (dashed curve). The Θ^+ production cross section was calculated for $\Gamma^{\rm tot} = 5$ MeV. The background was integrated over a range of ± 10 MeV around the K^+n missing mass of 1540 MeV.

2 Experimental Details

2.1 Overview

We propose to measure $\gamma D \rightarrow \Theta^+ \Lambda$ reaction in Hall A. Bremsstrahlung photons, produced by the electron beam passing through a photon radiator, will impinge on a cryogenic deuterium target. The maximum energy of the bremsstrahlung beam is essentially equal to the incident electron kinetic energy. The incident flux, using the 100 MeV tip of the spectrum, is typically 5 orders of magnitude larger than the tagged beam used for previous studies.

The cryogenic deuterium target, downstream of the radiator, is irradiated by the photons and the primary electron beam. The outgoing proton, from the Λ decay is detected in one of the two HRS spectrometers, set for positively charged particles in coincidence with the negative pion detected by an array of plastic scintillators. These counters will be set with very large energy deposition threshold to reduce the singles rates of low energy charged and neutral particles while allowing them to detect the very large deposited energy of the absorbed negative pion (Δ E above 140 MeV). The K^+ emitted from the Θ^+ decay will be detected by the BigBite large acceptance spectrometer of Hall A.

2.2 Choice of Experimental Hall

The need to measure a low cross section reaction and to determine the momentum and angle of the outgoing particles with high accuracy, makes Hall A the ideal choice for this proposal. The experiment can also be done in Hall C, but the existing infrastructure and experience in operating BigBite in Hall A makes that Hall the preferred location for this measurement. The large solid angle and momentum bite of BigBite are essential in order to detect enough of the Θ^+ decays.

This experiment cannot be done in Hall B due to the limited luminosity available and the insufficient resolution. Previous CLAS measurements show a limit of about 10 MeV missing mass resolution. This proposal aims for an order of magnitude better resolution.

2.3 Beam energies and conditions

The threshold for the Θ^+ photoproduction on a deuteron in the discussed reaction is about 1 GeV. We propose to do the measurements a couple of hundred MeV higher at at a beam energy of 1.2 GeV. The SAPHIR data shows that the $\gamma + p \rightarrow K^+ + \Lambda$ cross section is highest at this photon energy[14]. Also it is important to emphasize that the interference with the $\gamma + n \rightarrow K^0 + \Lambda$ amplitude significantly enhances the resulting cross section at the photon energy of 1.2 GeV (See Figure 2). It is also important that, by operating close to threshold and requiring the production of the $\Lambda(1115)$, we eliminate many possible sources of kinematical reflections that might in principle contaminate most other measurements.

2.4 Photon radiator

We propose the use of an untagged photon beam. Although tagged photon beam experiments are generally desirable, the technique is not suitable for small cross sections measurements. Our previous untagged measurements in Halls A and C have agreed well with tagged measurements, where an overlap was possible.

The radiator we plan to use is copper with a 6% radiation length thickness. The radiator will be set upstream of the target so that the HRS will not view it directly. We will shield the scintillator array from direct particles coming from the radiator. The energy loss in the copper radiator is about 125 watts for a beam current of 50 μA. A radiator similar to this, with the standard cryotarget beam raster, has been used in earlier Hall A photoproduction experiments.

2.5 Target

We propose to use the 15-cm long Hall A liquid deuterium cryotarget. The longer target will be used to reduce the end cap background. With the proposed 50 μA beam the power loss in the target is about 250 watts which is within the normal operational range of the target which has been operated at currents above 100 μA before. Density fluctuations of a few percent are expected for this beam current, but are irrelevant for this measurement.

2.6 Spectrometers

We will use one of the two Hall spectrometers (HRS) to measure the forward protons. This measurement requires no changes from the standard electronics and operation of the spectrometer. For this spectrometer we assume an angular acceptance of $\pm 1.6^\circ$ in the horizontal plane and $\pm 3.5^\circ$ in the vertical plane. A momentum acceptance of $\pm 4.5\%$ and a momentum resolution of $\Delta p/p = 10^{-4}$ were assumed for the simulations.

For the detection of the K^+ we plan to use the BigBite spectrometer with the drift chambers that will be used by upcoming low momentum hadron experiments. In addition to the PID offered by the E ΔE and the TOF versus momentum determined from the trajectory in the magnetic field, we plan to use a 2.1 m by 0.5 m aerogel Cherenkov (n=1.05) which is in storage at JLab. It will need work to be brought back into operation, but it is certainly usable and fits nicely behind the BigBite detector package with the chambers and the scintillators. With BigBite we assume that the K^+ will be detected over an angular range of $\pm 4.6^\circ(\pm 17^\circ)$ in the horizontal (vertical) planes with momentum resolution of $\Delta p/p = 10^{-2}$.

2.7 Scintillator Array

For the Gen and the SRC experiments we already have on site plastic scintillators bars with a cross section of 10-15x100 cm^2 and lengths of 1-1.6 m. These plastic scintillators have two PMs, one on each side. With a typical time resolution better that 200 ps, the signals from both sides can translate to position along the bar with typical resolution of $\sigma = 5$ cm, corresponding to 0.3° at 10 m. The TOF (momentum) resolution $\Delta p/p = \Delta\mathrm{TOF}/\mathrm{TOF}$

is better than 5×10^{-2} for 0.5 GeV/c, $\beta = 0.7$ particles, with the array at about 10 m. We plan to set the counters vertically perpendicular to the scattering plane which defines scattering angle bins of 10 cm (0.6° at 10 m). Negative pions of up to 200 MeV (see table 2) are stopped in the 10 cm plastic and deposit more than 140 MeV of energy. The threshold of these counters will be set very high (about 100 MeV) to minimize the singles rates. A special frame to hold the counters vertically is the only element of this array that needs to be custom made for this measurement. From the experiments mentioned above, the counters, high voltage supplies and distribution system, readout and fast electronics are available for more channels than are needed.

3 Kinematics and Requested beam time

3.1 Kinematics

As discussed above, we propose to do the measurement about 200 MeV above threshold with a photon beam of 1.2 GeV/c. Guided by the calculations of V. Guzey and M. Polyakov[15] and by the experimental constraints, we propose to do the measurement with the Λ produced at about 40° in the c.m. system (Θ^+ at 140° c.m). We will put the HRS between the Λ direction and the beam at an angle of 13°. Notice that this geometry can be measured both with and without the septum. The π^- will be detected on the other side of the Λ direction at relatively large laboratory angles (55-75°). See Figure 7 for an overview of the kinematics and the layout.

- $E_\gamma = 1.2$ GeV
- $s = 8.019396$ GeV^2, $W = 2.831854$ GeV, $t = -0.098(\mathrm{GeV}/c)^2$
- for Θ^+: $\theta_{\rm cm} = 140°$, $p_{\rm cm} = 0.482$, $p_{\rm cm}^{\perp} = 0.310$ GeV/c
- for Λ: $p_{\rm lab} = 0.97$ GeV/c, $E_{\rm lab} = 1.48$ GeV, $\theta_{\rm lab} = 18.8°$
- for Θ^+: $p_{\rm lab} = 0.42$ GeV/c, $E_{\rm lab} = 1.6$ GeV, $\theta_{\rm lab} = 48.1°$

We put the HRS at 13° with a central momentum of 0.873 GeV/c. See Table 1 for the proton kinematics.

The scintillator array covers the range 55-75° in the scattering plane and $\pm 3°$ vertical to the scattering plane. The array is on the same side of the beam as the HRS. See Table 2 for the π^- kinematics.

BigBite will be placed at $97 \pm 4.6°$. See Table 3 for the K^+ kinematics.

3.2 Resolution of reconstructed quantities

To estimate the expected resolution of reconstructed quantities like the photon energy, the invariant mass of the Λ and the missing mass of the Θ^+ we made the following assumptions as presented in Table 4. We assumed gaussian distributions using the quantities in the table

Table 1: *PROTONS:* $\Lambda^0 \to p\pi^-$ decay. $\theta_{\rm cm}$ the angle between the proton and the Λ^0 direction in the Λ^0 rest frame. The last two columns are the laboratory angles of the proton with respect to the Λ and the beam respectively.

$\theta_{\rm cm}$	momentum	energy	$\theta_{p-\Lambda}$	$\theta_{p-\rm beam}$
deg	[GeV/c]	[GeV]	deg	deg
45	0.919	1.313	4.4	14.4
60	0.893	1.295	5.6	13.2
75	0.862	1.274	6.5	12.3
90	0.828	1.251	7.0	11.8

Table 2: *PIONS:* $\Lambda^0 \to p\pi^-$ decay. $\theta_{\rm cm}$ the angle between the proton and the Λ^0 direction in the Λ^0 rest frame. The last two columns are the laboratory angles of the pion with respect to the Λ and beam respectively.

$\theta_{\rm cm}$	momentum	energy	$\theta_{\pi-\Lambda}$	$\theta_{\pi-\rm beam}$
deg	[GeV/c]	[GeV]	deg	deg
45	0.090	0.166	52.0	70.8
60	0.120	0.184	46.3	65.1
75	0.151	0.205	40.11	58.9

Table 3: $\Theta^+ \to K + n$ decay. $\theta_{\rm cm}$ the angle between the K^+ and the Θ^+ direction in the Θ^+ rest frame. The last two columns are the laboratory angles of the kaon with respect to the to the Θ^+ and beam respectively.

$\theta_{\rm cm}$	momentum	energy	$\theta_{K-\Theta^+}$	$\theta_{K-\rm beam}$
deg	[GeV/c]	[GeV]	deg	deg
60	0.375	0.620	38.6	86.7
75	0.345	0.602	49.1	97.2
90	0.310	0.583	60.4	108.5

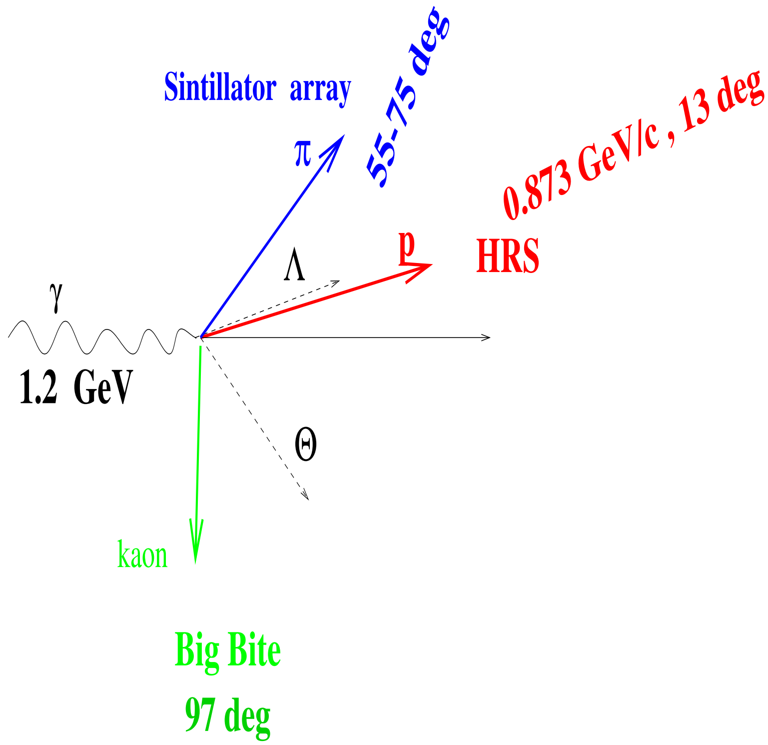

Figure 7: The proposed kinematics and experimental setup.

for the standard deviations of the distributions. The only exception is a uniform distribution assumed for the horizontal angle in the scintillator array. The quantity in the table in this case represents the angular range of a single counter (10 cm at 10 m from the target).

A simulation of 1000 events with the resolutions above is shown in Figure 8. The simulated distributions were fitted to gaussian distributions. The results of that fit are shown in the figure. For the simulation, the Θ^+ was assumed to be at 1540 MeV with a zero width. The width in the figure result from the experimental uncertainties only. Note that energy loss (straggling) in the target, small angle multiple scattering in the target, and beam divergence were not included in the simulations shown in Figure 8.

The upper left panel in Figure 8 shows the photon energy reconstructed from the measured momentum of the proton, pion, and kaon. This can be done with a resolution of about 3 MeV (σ).

The invariant mass of the Λ as reconstructed from the measured proton and pion momenta is shown in the upper right panel. The reconstructed mass has a resolution of about σ=0.3 MeV.

The Θ^+ missing mass reconstructed from the proton, pion and kaon momenta has a resolution of about 2.5 MeV (σ) as shown in the bottom panel of Figure 8.

The sensitivity of reconstructed quantities to detector performance was studied. Increasing the standard deviation for the horizontal proton angle detection by a factor of 4 and for the pion and the kaon by a factor of two has a small impact on the resolution of the photon

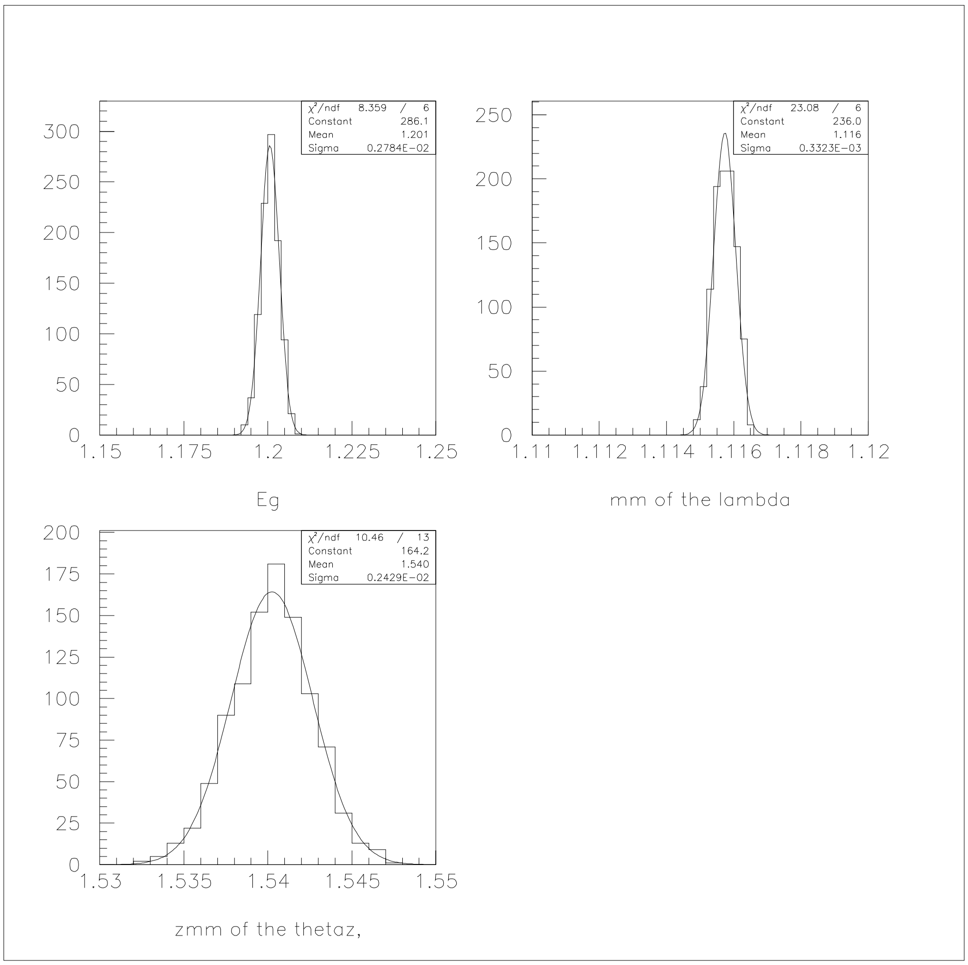

Figure 8: The reconstructed photon energy, Λ invariant mass, and the missing mass of the Θ^+. We assume in the simulation that the Θ^+ width is zero. The width shown is due to experimental uncertainty only. See text for details.

Table 4: Momentum and angular resolutions of the detection devices. The quantities in the table are the assumed standard deviations.

Device	particle	momentum	horizontal angle	vertical angle
		$\Delta p/p$	mr	mr
HRS	p	1.5×10^{-4}	1.5	4
Sci.	π^-	5×10^{-3}	10	5
BigBite	k$^+$	10^{-2}	5	5

energy and Θ^+ missing masses. The resolution for the invariant Λ mass is about doubled. Increasing the standard deviation of the proton momentum measurement by a factor of 10 and for the pion and the kaon by a factor of two has small effect on the resolution of the invariant Λ mass but almost doubles the resolution of the photon energy and the Θ^+ missing mass reconstruction. Doing both of these changes in momentum and angular resolution together, roughly doubles the widths of all reconstructed quantities due to the experimental uncertainties.

3.3 Triple coincidence rates

Count rates have been calculated based on the following assumptions:

- The photon flux was calculated for a 6% copper radiator using a thin radiator code. The typical number of photons is of order 10^{11} photons/second per 100 MeV photon beam energy bin for 30 μA. We used 50μA in the time estimates.
- The target areal density is $15 \times 0.17\text{g/cm}^2$.
- The effective solid angle of the HRS spectrometer is 4 msr when using the extended target.
- The neutron array will detect any π^- that is within its angular range and has not decayed. We assume that the pions decay and are lost from the detected flux with the known life time.
- BigBite is assumed to have an angular acceptance of $\pm4.6°(\pm17°)$ in the horizontal (vertical) planes. A K^+ of any momentum entering this range was assumed to be detected.

The Θ^+ production rate as a function of the production cross section is given by:

$$N = N_\gamma \cdot d\sigma/dt \cdot \Delta t \cdot N_d \cdot 3600. \tag{4}$$

where $N_\gamma = (5/3) \cdot 10^{11}$ for the tip with $E_e - E_\gamma < 100$ MeV, and

$$N_d = \frac{0.17 \cdot 15 \cdot 6 \cdot 10^{23}}{2} \mathrm{cm}^{-2} = 8 \cdot 10^{23} \mathrm{cm}^{-2}. \qquad (5)$$

The proton from the Λ decay is emitted (within 7°) in nearly the same direction as the Λ. Therefore, detecting the proton with a limited acceptance spectrometer results in a limited t-range. Detecting the protons with the HRS at 13° with respect to the beam limits the Λ to $38 - 45°$ c.m. angle, $18 - 21°$ laboratory angle, and t between -0.143 and -0.081 (GeV/c)^2 i.e. $\Delta t = 0.06$ (GeV/c)^2.

For the production cross section we used the calculations by V. Guzey and M. Polyakov as presented in detail in section 1.3. From Equation 1 one gets:

$$d\sigma/dt \cdot \Delta t = (12 \cdot \Gamma^{\mathrm{tot}}/5) \cdot 0.06 = 0.144 \cdot \Gamma^{\mathrm{tot}}[\mathrm{nb}] = 0.144 \cdot \Gamma^{\mathrm{tot}} \cdot 10^{-33} \mathrm{cm}^2. \qquad (6)$$

The Θ^+ production rate into the t range covered by the experimental setup is:

$$N_{\Theta+} = 0.07 \times 10^6 \cdot \Gamma^{\mathrm{tot}}/\mathrm{hour}. \qquad (7)$$

Not all the the protons from the Λ decay in this limited t-range are detected by the HRS due to its limited angular range. The protons from these decays cover a solid angle of about 60 mSr. Assuming that in this solid angle the protons are distributed evenly, the HRS with its effective solid angle of about 4 msr, will detect about 6.7 % of the protons. The π^- particles emerging in coincidence with these protons will all be in the solid angle covered by the scintillator array. A typical pion will have a momentum of about 180 MeV/c ($\beta = 0.78$) and therefore a TOF of about 42 ns from the target to the scintillator array. Thus only about 20 % of them will survive without decay (exp(-42ns/26ns)). Taking into account the detection of both a proton and a π^- will therefore lead to detection of about 1.3 % of the produced Λ particles.

The Θ^+ decay will produce a K^+ nearly isotropically. The BigBite spectrometer with a solid angle of about 96 mSr will detect about $96 \times 10^{-3}/4\pi = 0.8\%$ of these kaons. In addition, the K^+ rate will be halved due to the branching ratio assuming equal decay of the Θ^+ to charged and neutral kaons.

To summarize, the expected rates for the predicted production cross section and the selected geometry) are:

- Λ^+ production followed by a detection of the p, π^-: $900 \cdot \Gamma^{\mathrm{tot}}$ / hour. Notice that the Λ^+ rate is only for these produced in the $\gamma D \rightarrow \Theta^+ \Lambda$ reaction.

- Θ^+ production followed by a detection of the p, π^- and K^+: $3.7 \cdot \Gamma^{\mathrm{tot}}$ / hour.

Table 5: Summary of the required beam time.

Measurement	Time [hr]
Setup and calibrations	*50*
Measurement at 1.2 GeV	*100*
Radiator-out measurements (10% of the radiator-in time)	*10*
TOTAL REQUESTED BEAM HOURS	*160*

3.4 Summary of the required beam time:

We request 2 days for setup, calibration, establishing triple coincidence and about 4 days of measurement. If the cross section is as predicted, we expect to detect 370, 730, 1800, and 3650 events if the Θ^+ width is 1, 2, 5, 10 MeV respectively. In addition to the data runs, we propose to run a short run without a radiator to check the background rates. The beam time request is summarized in Table 5.

3.5 Background and Signal to Background Ratio

Using the 100 MeV/c tip of the photon beam energy, and a cut on the invariant Λ mass, limits the possible background processes. Only $\gamma D \to \Lambda K^+(n)$ processes are allowed. Production of additional mesons leads to the photon energy being reconstructed out of the allowed endpoint region. For invariant mass of the $K^+(n)$ in the vicinity of 1540 MeV and t at about -0.1 $(\mathrm{GeV}/c)^2$ the number of background events per 1 MeV missing mass bin is (See Figure 6):

$$\text{BG events(in 1 MeV bin)/total signal events}(\Gamma^{\text{tot}}\text{=5 MeV}) = 1/(2\times 20)\ \text{[events/MeV]}.$$

Table 6 shows, for Θ^+ widths of 1, 2, 5, and 10 MeV, the number of Θ^+ particles produced (N_{Θ^+}), the number of background events integrated over a missing mass bin of $\pm 2 \times \sqrt{(\Gamma^{\text{tot}})^2 + 2.5^2}$ (N_{BG}), and the ratio $N_{\Theta^+}/\sqrt{N_{\Theta^+} + N_{\text{BG}}}$. We also show the cases that correspond to the same background as above, but with production yield suppressed by an order of magnitude compared to the calculations. Notice that if the Θ^+ width is above 5 MeV, even if the production cross section is an order of magnitude lower than the prediction, we can establish a peak of about 150 events with statistical significance level of about 5 standard deviations and a well-determined width. However, if the width is about 1 MeV, and the production cross section is suppressed by an order of magnitude, we only obtain statistics similar to the existing first-generation experiments.

Table 6: Signal (N_{Θ^+}), background ($N_{\rm BG}$) and signal/background ratio ($N_\theta/\sqrt{N_\theta + N_{\rm BG}}$).

$\Gamma^{\rm tot}$ (MeV)	production cross section	N_{Θ^+}	MM range (MeV)	$N_{\rm BG}$	$N_\theta/\sqrt{N_\theta + N_{\rm BG}}$
1	calc.	370	11	500	12
2	calc.	730	13	600	20
5	calc.	1800	22	1000	35
10	calc.	3650	41	2000	50
1	calc./10	37	11	500	1.5
2	calc./10	73	13	600	3
5	calc./10	180	22	1000	5
10	calc./10	365	41	2000	8

4 Related Experiments

There is an approved Hall B proposal to repeat the deuteron measurement with enough beam time to establish a peak of about 800 events under the same conditions that the previous peak was observed. This measurement, if it yields the expected peak and can be shown not to be due to kinematical reflection, can be a confirmation of the Θ^+'s existence. That Hall B experiment cannot compete with this proposed experiment on the measurement of the Θ^+'s width. The mass reconstruction resolution is an order of magnitude worse than for this proposed measurement.

There are other proposals being submitted to PAC 25 for both Hall A and Hall C concerning the Θ^+. The Hall A proposal is designed, similar to this proposal, to produce and measure the width of the Θ^+, but using electroproduction rather than photoproduction. The expected rates and resolution are similar and the experimental setup has much similarity. Since the production mechanism for the Θ^+ is not well known and since both of these proposal are "fishing expeditions" in nature, we believe that a short test for both reactions (together) might be an appropriate strategy.

5 Collaboration and needed resources

The current collaboration is composed of many members who have already done real photon measurements in Halls A and C. This collaboration has the necessary expertise and personnel for operating the experiment and analyzing the data. We are also working closely with theorists. V. Guzey and M. Polyakov carried the calculations used to design the proposed measurements and no doubt will also take a major role in understanding the results.

Due to time constraints we did not submit this proposal to approval as an Hall A collaboration proposal. We intend to do so as soon as possible. We welcome any Hall A users that wish to join the experiment and contribute to its success.

The experiment uses existing equipment at the laboratory. A new frame for the scintillator array will be required. Rebuilding the Cherenkov detector and constructing a new frame compatible with BigBite, will also be required. The experiment will require a few days of setup time in Hall A, depending on the status of the spectrometers and cryotarget prior to the start of the experiment.

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